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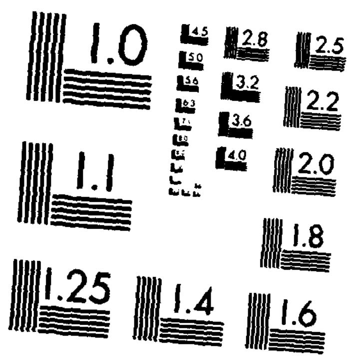

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MENTAL MODELS FOR MECHANICAL COMPREHENSION: A REVIEW OF LITERATURE

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2. Mental models for mechanical comprehension being produced by recent research in cognitive psychology offer many new insights for developing new computerized ability tests that will improve prediction of job performance. This work is relevant to testing human abilities in problem solving, and separating mental abilities into distinct elements.

Martin F. Wiskoff

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This literature review describes the recent research on mental models of mechanical comprehension. Three methodological approaches (constructionism, information-processing, and componential analysis) are discussed in terms of strengths and weaknesses. Variables shown to affect problem solving include pictorial representation, naive preconceptions about motion, the use of analogies, and the educational level of the problem solver. The theoretical concepts for describing the ability to solve problems include envisionment, assimilation-accommodation, and the space factor, "S." Further research possibilities are described.

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SUMMARY

Problem

The Navy is presently designing computer-based testing systems for new recruits. One important ability that needs to be tested is the ability to understand the forces acting on objects in motion. This is a subfield of mechanical comprehension. Presently, validities on the mechanical comprehension subtest of the ASVAB range from a high of .75 to a low of .30 or less, leaving much room for improvement. To assist in improving this validity, the literature dealing with solving physics problems, which concern objects in motion and the accompanying forces, was reviewed.

Objective

This literature review summarizes studies of the mental models that people use to understand and solve problems involving mechanics and motion.

Method

The existing psychological literature on mental models for the comprehension of objects in motion was searched. References that were the most general or that generated the most citations in later works were selected for annotation.

Findings

Historically, Thurstone's concept of the space factor, "S," was the most salient contribution before the 1970s. This factor linked spatial ability to the ability to solve mechanical problems. Modern investigations have resulted in the theory of "envisionment," a process that "runs" a mental simulation of a physical mechanism, a simulation that constitutes a dynamic mental model.

Three approaches have been used to investigate mental models. The constructionist school is concerned with how mental models are formed. The information-processing school uses the experimental methods of modern cognitive psychology to investigate mental structures. The componential approach attempts to meld the information-processing approach and the classical factor-analytic approach in order to separate mental abilities into distinct elements.

This review concentrates on the componential approach. Four classes of variables are considered: (1) Pictorial representations of a problem, (2) the vast number of preconceptions that people bring to a problem situation, (3) the use of analogies in mental models, and (4) the educational history of an individual.

The annotated bibliography follows the literature review.

CONTENTS

INTRODUCTION

Problem

The Navy is in the process of designing computer-based systems for testing its recruits. One important ability that needs to be tested is the ability to understand forces acting on objects in motion--for example, how gears work or the path of an object dropped from a plane. Presently, validaties on the mechanical comprehension subtest of the ASVAB range from a high of .75 to a low of .30 or less, leaving much room for improvement. To this end, the research on solving physics problems about motion and the accompanying forces needs to be summarized for use in testing system design.

Objective

This literature review summarizes research on the mental models that people use to understand and solve problems of mechanics and motion.

METHOD

The psychological research literature on mental models for the comprehension of motion was searched and the most seminal studies were chosen for annotation. The studies chosen either provided the most general discussions of mental models or were among those most often cited in the post-1980 literature.

REVIEW OF THE LITERATURE

Defining Mechanical Problems

In the broadest sense, the term "mechanical problem" encompasses those that involve either static objects or objects in motion. Therefore, mechanical problems involve either potential energy or kinetic energy. Some problems ask a subject to describe an object's motion, and some ask a subject to predict the effect of a force or forces. This review gives special consideration to problems presented on a cathode ray tube (CRT), with or without animation.

The ability to solve mechanical problems and the ease of their comprehension are based on the mental models that people use. Mental models qualitatively model a physical system. They are composed of autonomous objects with an associated topology. They are "runnable" by means of local qualitative inferences and they can be broken down into component parts (Williams, Holland, & Stevens, 1983). All this means is that mental models have parts that can stand alone and can be related to other parts of the model in some logical fashion.

Peoples' views of the world, of themselves, of their own capabilities, of the tasks they are asked to do, and of the topics they are asked to learn depend on the conceptualizations they bring to these acts (Norman, 1983). These conceptualizations--mental models--guide peoples' use of things.

An important issue in the study of mental models for military purposes is the relationship of models to mechanical and spatial problem-solving. The first goal of this review is the specification of these mental models. This will allow a tailored approach to testing and measurement that may improve the classification of recruits. Foremost in researchers' minds are questions such as, "What is the nature of the mental models people form when solving mechanical or physics problems?" and "How do they use these models to solve the problems?" It is necessary to determine what components make up the ability to solve mechanical problems and then determine how differences in these components affect differences in ability.

The mechanical problems of interest are extremely diverse, but almost all involve objects in motion. The different kinds of motion involved include linear motion (Trowbridge & McDermott, 1980, 1981), circular motion (McCloskey, 1980, 1983), projectile motion (Champagne, Klopfer, & Anderson, 1980; Clement, 1982), trajectories of falling objects (Caramazza, McCloskey, & Green 1981; Clement 1983; diSessa, 1982; McCloskey, Washburn, & Felch, 1983), spinning objects (diSessa, 1983), and various other kinds of physical motion (diSessa, 1983; Forbus, 1981, 1983; McCloskey, 1983a). The problems themselves range from understanding meshing gears to predicting the path of an object dropped from a plane.

Any understanding of objects in motion presupposes an understanding of forces, so we are interested in how people attempt to understand forces. Investigations into mental models have concentrated on several areas. For example, many researchers have concentrated on how people come to understand and use Newtonian physics to reason about objects in motion (Larkin, McDermott, Simon, D. P., & Simon, H. A., 1980a, 1980b; Minstrell, 1982; Trowbridge & McDermott, 1980, 1981; White, 1983). Other researchers have concentrated on "Aristotelian" physics, which refers to beliefs that objects in motion must always have a force present moving them and that all motion must have a directly discernible cause (diSessa, 1982, 1983; Fuller, 1982; McCloskey, Caramazza, & Green, 1980; McCloskey, 1983a, 1983b). This pre-Newtonian theory of motion, sometimes referred to as "impetus" theory, is apparently a common "intuitive" theory of motion (see McCloskey 1983a, 1983b). McCloskey and colleagues have concluded that subjects' judgments about the paths of moving objects are systematic, arising from a general, coherent theory of motion that closely resembles this pre-Newtonian, Aristotelian impetus theory. The "cause" appears to represent an internal impetus that would gradually dissipate. For example, people describing a child pushing a toy across the floor commonly use the "impetus" theory: They say that the child imparted a "force" on the car with his hand, and the reason that the car stops is not the friction of the floor, but rather the dissipation of the energy that the child had given to the car.

The similarity between the descriptions of naive persons living today and those of the medieval philosophers suggests that the impetus theory is a natural outcome of experiences. A. A. diSessa (1982) concluded that a "special layer" of primitive notions in people serves as the foundation for a system of knowledge about motion. He calls these notions "phenomenological primitives," which are derived from real world experience and help people explain the world around them. Viennot (1979) had a similar conclusion--that we all have an intuitive sense of the physics of motion.

Intuitive physics may interfere with effective instruction in real physics. Viennot demonstrated that many people believe in a linear relation between force and velocity, as impetus theory would suggest, rather than the correct linear relation between force and <u>acceleration</u> (see also Trowbridge & McDermott, 1980, 1981). In other words, most people believe that an object moving at a constant speed is being moved by a constant force, when in fact a body <u>accelerates</u> if a constant force is applied.

Historical Background

The understanding of motion (mechanical comprehension) has been linked to spatial ability (Thurstone, 1951). Numerous factorial studies reveal a spatial factor that is distinct from verbal ability, beginning with Kelly's (1928) identification. The seminal contribution was Thurstone's space factor, "S," the ability to visualize objects in space (Thurstone, 1938, 1944, 1947, 1951; Thurstone & Thurstone, 1941).

Modern analysis of Thurstone's "S" has shown that at least two distinct mental abilities contribute to it. The first is visualization, the ability to mentally manipulate the elements of a pattern. The second is orientation, the ability to determine spatial orientation with respect to one's body (McGee, 1979; Pylyshyn, 1973). Thurstone anticipated this division by breaking down "S" into component parts. His factor analysis found that "S" was made up of at least three distinct abilities, two of which were remarkably similar to modern theory. Thurstone's first space factor component represents the ability to visualize a rigid configuration when it is moved into different positions. The second space factor component represents the ability to visualize a configuration in which there is movement or displacement among the parts of the configuration. Thurstone was unable to interpret the third space factor because of its association with only a small number of tests.

The modern counterpart of Thurstone's "S" is de Kleer's (1981) theory of envisionment. Envisionment is a mental process that runs a qualitative simulation of a physical mechanism that results in a dynamic mental model (de Kleer, 1981). Envisionment combines aspects of both visualization and orientation. The resultant mental model is a combination of an envisionment and its causal attribution. One need to cognitive science is to describe exactly what we mean by the "mental model" that results from envisionment. Newell, Simon, and Shaw (1960) and others (Norman, 1983; Williams et al., 1983) are interested in (1) what it means for a person to understand a complex system--in particular, the mental models that experts form of how a system functions, given the system's constituents and their interconnections; and (2) the principles governing acquisition of the ability to construct these models (de Kleer & Brown, 1981).

We must assume that people who solve problems are using some mental model of processes, even if they construct the model only when we present the problem. One fundamental ability for solving physics problems is the ability to picture mentally, or use what is commonly called "the mind's eye" on just what the problem entails (Kosslyn, Cave, Forbes, & Brunn, 1983; Shepard & Chipman, 1970; Shepard & Metzler, 1971; Shepard & Feng, 1972; McCloskey, 1983a, 1983b; McCloskey et al., 1980). The imagining is not necessarily the same as planning how to solve the problem, nor is it actually the same as the solving the problem. In the simplest case, it is imagining what has happened in the problem described, or imagining what will happen if the constraints of the problem are fulfilled. As the problem becomes more complex, involving motion over a longer period of time or involving more interactions of objects, the imaging process also becomes more complex.

General Approaches to the Study of Mental Models

What are the general approaches to the study of mental models? A wide variety of experimental designs have been used. There are at least three major schools of thought. The constructionists are concerned with how mental models are formed. Jean Piaget, the first constructionist (for a review, see Piaget, 1970), conceptualized mental advancement as based on a model of assimilation-accommodation, the foundation for rationality. This assimilation-accommodation model assumes that as a child grows he constructs "schemata" of the world into which all new information is gathered. If a child's structures can include a new fact about the world without change in the structures, Piaget says the child had assimilated the information. If, on the other hand, a child's structures cannot assimilate the new fact in the present form, then the structures must change. Piaget calls this process accommodation. Taken together, these two processes are responsible for mental development.

The second major school of thought is generally called the information-processing approach (Egan & Grimes-Farrow, 1982; Forbus, 1981; Fuller, Karpus, & Lawson, 1977; Gentner, 1980; Goldin & Thorndyke, 1981; Larkin et al., 1980b; Newell et al., 1960; Norman, 1983). This is the general approach of modern cognitive psychology. Its investigators have attempted to describe, through experimentation, the way in which people solve problems. Experiments involve reaction times, classification of words into various categories, and simple verbal descriptions of subjects attempting to describe physical situations. Experiments also compare the performance of novice and expert problem solvers. Both the constructionist school and the information-processing school have used factor analysis in attempts to isolate crucial factors of human spatial ability, but the information-processing approach has done so to a much larger degree (Sternberg, 1977).

The third and most recently appearing school of thought on mental models of mechanics is the componential (McGee, 1979; Sternberg, 1977). The componential method subdivides mental models into separate processes of mental ability, as did, for example, Thurstone's visualization and orientation components. The componential approach investigates hypothesized mental abilities using experimental methods common to cognitive psychological research. In the last 20 years, this third type of analysis, which examines processes common to all individuals rather than factors reflecting individual variance, has come into favor over factor analysis. Researchers of the componential school have attempted, at least in theory, to combine the strengths of both the factor-analytic and the information-processing approaches into one theoretical basis for investigating mental models (Sternberg, 1977). This is the approach being reviewed.

Constructing and Using Mental Models

How do we determine the effectiveness of mental models? How well are they used by different subjects? The information can be partially gleaned from performance measures, but other methods are also available.

J. de Kleer (1981) discovered at least two principles for construction of a good mental model. The first is qualitative simulation that does not presuppose the very mechanism it is trying to describe. Agreement with the principle is achieved by having the model satisfy a constraint called the "no-function-in-structure" principle (de Kleer, 1981). It states that the rules for specifying the behavior of any part of the system cannot refer to how the overall system functions. The principle was designed to assure that the envisionment avoids the trap of teleological reasoning. The second principle, "weak causality," states that every event must have a direct cause, meaning that the reasoning process determining the next state change is local and does not use any indirect argument in determining what the next state must be.

According to de Kleer, the process of trying to understand the functioning of some mechanical device is like solving a traditionally presented (i.e., a textbook type) physics problem, because both real-life and textbook problems can be solved by constructing a mental model. J. de Kleer refers to these mental models as "envisionments." Simply put, an envisionment is a dynamic mental model of some system or device. For example, most of us can envision a fairly good model of our solar system. The model contains planets, sun, etc., and can be used to determine how the planets move in relation to each other and to the sun. Imagining the planets in motion is what de Kleer calls the "running" of a mental model.

Variables that Affect Problem Solving

Pictures. Physics problems are often accompanied by a picture, abstract schematic, or animation on a computer screen. How exactly do people construct images in their minds using these external memory aids? One important insight comes from the observation that when physics problems do not have illustrations, expert problem solvers, and often novices as well, almost invariably draw a picture (Kosslyn et al., 1983). Clearly, a picture is a key part of understanding many types of problems. Pictorial representation is a general term--the representations can range from still pictures to animation of complex processes.

But a sketch is often a far cry from a solution. For easier problems, a sketch may be a major step; for more difficult problems, a sketch may be only a small part of the solution, perhaps aiding only in the organization of information (i.e., the information presented in the question). Using the picture to solve the problem is an additional event (de Kleer & Brown, 1981). Thus, the use of external memory aids for problem solving has at least two parts. First, you have to understand the information in the picture, and second, you have to use your understanding of the picture to solve the problem. The same requirements apply to the mental pictures of envisioning. Once you have envisioned a problem, you must then "run" your envisionment to produce useful information (de Kleer, 1981).

Naive Beliefs. Another important factor in problem solving is the vast number of preconceptions or naive beliefs about motion that people bring to the laboratory, classroom, or testing situation. These "intuitive preconceptions" (Clement, 1982) apparently arise from everyday experiences with moving objects. They are largely incorrect and highly resistant to change. For example, Clement (1982) tested 43 students with simple physics problems. After an introductory course in mechanics, they were tested again on the same problems. The scores were hardly better than the pre-course low levels, impling that these preconceptions are resistant to change. The stability and generality of preconceptions is also shown by the fact that a wide variety of physics novices make similar predictions, all apparently based on similar incorrect mental models. (See also diSessa, 1983, and his discussion of "p-prims"; and White, 1983, for a contrary opinion.)

Analogies. A third factor in the construction of mental models is the use of analogies (Gentner, 1980; Greeno, 1983; Young, 1983; Sternberg, 1977). Analogies clearly play a strong conceptual role in the description and understanding of many physical processes. For example, in instructing people about electricity, two analogical models of the flow of current can be presented. The first is that current behaves as flowing water; the second, that current flows as a teeming crowd (Gentner & Gentner, 1983). Gentner and Gentner (1983) cited two proofs of analogies' effects on peoples' conceptions of a domain: (1) they are widely used in teaching, and (2) working scientists often use analogies in theory development. These authors also showed that the inferences people make in a topic domain vary according to the analogies used to approach the problems.

Educational History. A person's educational history is clearly responsible for some variation in ability. Often, however, two people of about the same background receive instruction in a new topic and one person will pick it up rapidly while the other person has a much harder time applying the new information. The contributions of educational history are not yet clear, but they should be taken into account when designing experiments and interpreting results on mechanical comprehension.

One Ability or Many? But how do pictures, naive beliefs, analogies, and education, as well as any other factors we can discern, affect the individual's ability to envision a mechanical process? Are these the only factors affecting ability? How do the factors work together? Are other factors prerequisite to imagining? Kosslyn et al. (1983) asked whether people differ in terms of a general, undifferentiated imagery ability or in terms of a set of independent abilities. They found that imagery is not a single ability. Rather, it is a collection of distinct abilities, such as visualization and orientation, which are in turn are part of a larger constellation of spatial abilities. An interesting implication of this concept is that people's abilities for different sorts of problems are a function of component abilities. In other words, subjects high in analogical reasoning will do better on problems involving analogies, while subjects who are high in visualization ability will do better on tasks involving visualization.

Kosslyn et al. investigated the possibility of strategic control over the distinct abilities that make up imagery. They constructed a small subset of tasks that investigated one and only one of these components at a time. Although they investigated only a small portion of the constellation of abilities that make up imagery, this technique holds promise for further investigation of a larger class of variables. These possibilities for future research are explained in the discussion section concluding this review.

Running an Envisionment

The ability to envision a physical process is only part of solving a problem. An unanimated picture does not naturally represent motion. The human problem solver is, however, usually capable of what de Kleer (1983) called "running" the envisionment. One way of thinking about this is to see the model of a physical mechanism, and then put the model through its paces. In other words, we run the model through the actions that the mechanism is capable of. This ability is crucial to understanding how a system will function when running as planned. It also allows the subject to predict how the system will perform under new conditions.

Expert and Novice Problem Solving

Part of the approach of modern cognitive psychologists is to explore differences in the mental models of experts and novices. Expert or novice status is inferred from differences in performance (Larkin et al., 1980a; Larkin et al., 1980b; Larkin, 1983; Novak & Araya, 1980). Some researchers have concluded that experts and novices construct different mental models for the same problems (Chi, Feltovich, & Glaser, 1981), with the models involving different entities and rules. For example, a qualitative analysis of problem-sorting has shown that novices sort by "surface structures" of the objects in the problem (the literal terms mentioned or the configuration of the problem). Experts sort problems by the major physics principles required for solution (Chi et al., 1981). These observations lead us to the conclusion that envisioning or imagining the problem situation is important only if it aids understanding of the problem.

Problem-solving performance can be divided into at least two categories. First, performance depends on the reasoning aspects of the envisionment. Reasoning here refers to the internal and external consistency of the model. It must be free of internal contradictions and must accurately reflect the real world process under scrutiny. Second, there is performance that depends on predictive value of the model. It must not only predict the behavior of the system under stated conditions, but must also predict the behavior of the system under unforeseen perturbations.

How a model is used is important to a problem solution because its use must be correct (accurate) to produce the correct answer. To attain a correct answer using an incorrect model is a related interesting topic requiring investigation. A second aspect of novice/expert comparison is the use of multiple models. For example, do experts differ from novices only in having accurate models and running them faster, or do they differ qualitatively in the methods they have available to solve problems?

DISCUSSION

The issue of strategic control over the abilities which compose imagery ability can be investigated in a wider variety of experimental situations than implied by Kosslyn et al. Computer animation offers many approaches to the description of peoples' conceptions of motion.

Specifically, such a paradigm can be used to investigate peoples' conceptions of an object moving in a variety of ways. For example, we could produce equivalent problems that are presented in both "perfect Newtonian space" and in a more "real world" (i.e., frictional) environment. The research of A. diSessa has developed one interesting method for the investigation of ideas about motion using computer screen "dynaturtle" graphics. A dynaturtle is a graphics entity which is moved around the computer screen with typed commands. The turtle responds to the command RIGHT or LEFT by instantly turning 30 degrees in place. The dynaturtle acquires a velocity with a KICK command which gives it an impulse in the direction the dynaturtle is currently facing. To effect real time control, one normally directs a dynaturtle with single keystroke commands, R, L, and K which stand for right turn 30 degrees, left turn 30 degrees, and KICK.

The dynaturtle represents Newton's first law in that it remains at rest or travels at a constant speed in a straight line when no force is acting on it. This is the behavior of the dynaturtle when no KICKs are applied. It represents Newton's second law, symbolically Force = mass x acceleration, which specifies how velocity changes when a force is supplied: the vector change in velocity is proportional to the force and inversly proportional to the mass of the object. The mass of the turtle is constant and does not affect the representation. A KICK is a discrete version of a force and specifies the change of velocity according to the principles of vector addition. Newton's third law is not represented in this system (diSessa, 1982). The possibility along this line is to present subjects with problems in "impetus" space as well as "Newtonian" space; in other words, dynaturtle graphics that reproduce Aristotelian ideas of how forces affect the motion of objects. These graphics would include the idea of circular impetus, and the idea that motion implies that a force is present.

I suggest the presentation of the same problem should be varied by only one factor or specific ability that makes up the cluster of abilities that we refer to as the ability to imagine a problem situation. The effect (and validity) of the various factors can then be disentangled and more clearly understood. Another possible avenue of investigation would be to vary the mode of presentation of the same or similar problems. For example, the same problem could be presented orally, then in a static written mode, and finally on a comp: ter terminal. The various effects, if any, of the mode of presentation could then be determined.

But how are we to study the "running" of a mental model? Computer animation may help to explore the way people think about the different kinds of motions that an object can undergo while "running" an envisionment. I think we can begin to answer such questions as how to describe qualitatively and then quantify mental models of objects in motion using dynamic computer animation. By using diSessa's "dynaturtle" software, set up to operate in different modes, we can investigate how subjects learn about and understand objects in motion. For example, we might have three different "physics" for different dynaturtles; the first would be programmed to respond as a "perfect Newtonian world," with no friction and no gravity, another dynaturtle would react in a more "real-world" sense, with gravity and friction involved, and a third dynaturtle could be programmed to respond in an Aristotelian or impetus mode.

FINDINGS

The annotated bibliography that follows contains the seminal findings of the literature review. The following subheadings are used to guide the reader into the areas of concentration of the annotations:

Computer simulations of mental models

Expert and novice differences in mental models

Teaching and learning physics

"Impetus" or Aristotelian theories of motion

Analogical reasoning in mental models

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ANNOTATED BIBLIOGRAPHY

Computer Simulations of Mental Models

Bundy, A., & Byrd, L. (1983). Using the method of Fibres in Mecho to calculate radii of gyration. In D. Gentner & A. L. Stevens (Eds.), Mental models (pp. 253-266). Hillsdale, NJ: Erlbaum.

This article describes some of the more recent developments of the computer program MECHO, which was designed to solve mechanics problems written in English. By using a method described by Cohen (1974), you divide a body into an infinite number of subbodies, then you analyze a typical subbody. This method, called Fibres, was employed by MECHO.

Forbus, K. (1981). A study of qualitative and geometric knowledge in reasoning about motion (Technical Report No. 615). Cambridge, MA: Artificial Intelligence Laboratory.

The following central ideas are discussed:

1. Spatial reasoning.
2. Qualitative knowledge.
3. FROB (a computer program).
4. Geometric considerations.
5. The representation of motion in quantitative terms.
6. The representation of motion in qualitative terms.
7. Some summary remarks.

The author proposes the following questions about spatial reasoning: Why are people so good at reasoning about space? Why do computer programs not seem to capture this ability, such as algebraic manipulation and proving theorems? Forbus hypothesizes that the ability is based in our visual apparatus. The author notes that several different classes of problems involved in spatial reasoning are (1) navigation, (2) knot tying, and (3) motion problems. The author proposes that the most important factor common to all these problems is "place"--this is a piece of space where all parts of it share some common property.

The discussion turns to qualitative knowledge. The motion of an object can be described as a sequence of qualitatively distinct actions: first describe each action, then link the actions by descriptions of object before and after each action. The author refers to the description of possible motions generated by qualitative process of simulation as "envisioning." This process is domain dependent and makes heavy use of spatial descriptions.

A computer program, called FROB, was implemented to explore the issues of reasoning about what is called the "bouncing ball world." This "world" is merely a ball or balls bouncing about on a set of surfaces. FORB's description of the scene is made up of the following components:

1. Metric diagram: basic geometry representation.
2. Space graph: qualitative description of space.
3. Sequence graph: possible motions of a ball from a previous state.
4. Action sequence: actual motion of a ball.

Several geometric considerations are necessary to discuss motion problems. For example, when doing motion problems, people usually draw diagrams. These pictures serve as an organizing tool that helps make spatial arrangements explicit. It allows answers to some spatial questions by interpreting the information gleaned by perception. The geometry module answers three types of questions:

1. Identity concerns identification of an element in the geometric representation with the physical entities they model.

2. Parity concerns questions about spatial relationships between elements.

3. Intersection can be considered subset of parity. This is important because interacting physical constraints are usually reflected in diagrams by things that touch.

The representation of motion in a quantitative sense is discussed. The motion of object can be described by specifying coordinates in a frame of reference for each instant in time. Often these motion descriptions use equations that involve both quantitative and geometric knowledge.

The representation of motion in a qualitative sense is discussed. A description of motion is considered qualitative if it uses terms that reflect its essential features, such as position or elasticity. A good basis is to abstract the quantitative concept of state. If a state is defined properly, a set of rules can be defined that describe what *qualitative* states can occur after some other state. These rules can generate description of all possible motions from some initial state. The results of this process are called the "envisionment" for that state, which is imagining what can happen. A final consideration is the notion that qualitative spatial reasoning requires the notion of a place. A place is a connected subset of space in which some distinguished property holds true.

The author offers the following concluding remarks. This work has studied the role of qualitative and geometric knowledge in reasoning about motion. The issues were explored by building a program, FROB, that could reason about motion in a simplified domain. If metric properties for spatial aspects of a problem are provided, simple methods (paper and pencil diagrams) can be used to answer certain spatial questions. Qualitative reasoning about space requires dividing space into distinct places. Different descriptions of the same situation must have a common vocabulary for communication. Finally, this program must take into account the effects of assumptions about a ball and its motion.

Forbus, K. D. (1983). Qualitative reasoning about space and motion. In D. Gentner & A. L. Stevens (Eds.), Mental models (pp. 53-73). Hillsdale, NJ: Erlbaum.

The author discusses his work exploring issues involved in reasoning about motion. He suggests that one way to study this is to design a computer program that can answer the same sort of questions that we might ask about the domain of motion. To explore these issues, he has written a program called FROB, which is capable of answering many questions about the movements of a bouncing ball in an enclosed space. He notes that two aspects of human reasoning are missing from FROB--relevance and significance.

Just, M. A., & Carpenter, P. A. (1981). A preliminary proposal to ONR to develop simulation models of visual problem solving. Pittsburgh, PA: Carnegie-Mellon University, Department of Psychology.

The major goal of the proposed work is to develop simulation models of spatial problem solving, particularly psychometric tests of spatial ability and visual tests of intelligence. The goal is to model how humans solve problems (e.g., what they look at, what answers they give, and, moreover, the sequence and duration of their intermediate computations). The model will do the cognitive operations in the same order as people and will devote the same amount of processing effort (proportionally) to each stage that people devote.

Larkin, J. H., McDermott, J., Simon, D. P., & Simon, H. A. (1980b). Models of competence in solving physics problems. Cognitive Science, 4, 317-345.

This paper is an investigation into the domain of problem solving competence. Two computer programs capable of solving the same problems asked of expert and novice individuals in the field of physics have been built. The programs represent both naive and more competent problem-solving behavior.

The two models have a working memory. This is limited in capacity, containing about 20 elements, a plausible size for short term memory. The models have memory elements that execute the following functions:

1. Assign symbols to aspects of the problem description.
2. Select relevant physics principle.
3. Generate the corresponding equation.
4. Connect symbols in the equation of information in the problem.
5. Solve equations.

In addition to this information, both models have strategies that allows them to decide what to do next. The first strategy, referred to as Means-Ends analysis, corresponds to the method used by most novice solvers. This model works backwards, beginning with the desired quantity and then looking for equations that contain that quantity, looks at the current equation and the equation that will yield the answer, assesses the difference, and then tries to reduce it. The second strategy, referred to as Knowledge-Development analysis, corresponds to the method used by problem solvers with more skill. This model works forward, beginning with the known values in the problem, applies relevant equations, and derives new quantities until the desired quantity is reached.

Another difference is the way in which strategies are used. In the Means-Ends strategy, an equation is selected and written, and then variables are connected to known or desired variables specified by the problem. In the Knowledge-Development strategy, the selection and application of a principle have been combined to form a single step. Both of these are limited in that they do not allow planning or qualitative reasoning, nor can they handle simultaneous equations.

The results of the work done shows that the models did a good job of simulating the method of problem-solving used by the novices and the experts.

Newell, A., Shaw, J., & Simon, H. (1960). Report on a general problem-solving program. Proceedings of the International Conference on Information Processing (pp. 256-264). Paris: UNESCO.

This paper asks, what questions should a theory of problem-solving answer?

1. It should predict the performance of a problem-solver handling specified tasks.

2. It should explain how human problem-solving takes place--what processes are used and what mechanisms perform these processes.

3. It should predict the incidental phenomena that accompany problem solving and the relation of these to the problem-solving process. For example, it should account for "set" and for "insight."

4. It should show how changes in the attendant conditions--both changes "inside" the problem-solver and changes in the task--confronting him alter problem-solving behavior.

5. It should explain how specific and general problem-solving skills are learned and what the problem-solver has when he has learned them.

The following proof methods are suggested:

1. Substitution.
2. Detachment.
3. Forward chaining.
4. Backward chaining.

Some general characteristics of the problem-solving process are listed below:

1. Set--a readiness to make a specified response to a specified stimulus.
2. Insight--suddenness of discovery, grasp of the structure of the problem.
3. Concepts--concerns their formation-searching for similarity.
4. Hierarchies of processes--what proof method is tried when: This orders the approach to the problem.

Expert and Novice Differences

Caramazza, A., McCloskey, M., & Green, B. (1981). Naive beliefs in "sophisticated" subjects: Misconceptions about trajectories of objects. Cognition, 9, 117-123.

The experimenters questioned 50 undergraduates about the motion of a pendulum. The students were asked to draw the resulting path of the ball if the string on the pendulum is cut. Answers consisted of vertical and parabolic trajectories and varying horizontal displacements. The authors divided the responses into six categories.

1. Reasonable understanding of projectile motion.
2. Confused horizontal velocity.
3. Confused vertical acceleration and resulting parabolic path.

4. Ignored initial velocity of the ball.
5. Ball fell in the opposite direction from the string.
6. Dissipating "impetus" theory.

In categories 4, 5, and 6, the students had no evidence of any understanding.

Only 33 percent of the students who had completed high school and/or a college course in physics gave type 1 answers.

Goldin, S. E., & Thorndyke, P. W. (1981). An analysis of cognitive mapping skill (Technical Report No. n-1664-Army). Alexandria, VA: Army Research Institute.

Acquiring an accurate representation of the configuration (shape) and location of objects in the environment is a fundamental component of many spatial tasks. Several explanations for variabilitv in this skill have been proposed and are listed below:

1. Individual differences in visual memory and spatial restructuring abilities.

2. Differences in exploratory motivation and environmental interaction.

3. Individual differences in the amount or type of environmental experience available to the individual.

4. Differences in the strategies and processes/procedures people use to do a task.

This report compares the performance of good and poor cognitive mappers on a variety of spatial knowledge acquisition and judgement tasks. Subjects were categorized as good or poor cognitive mappers by measuring their knowledge of a highly overlearned environment, their home community. They were then compared experimentally on the tasks of learning a novel environment from navigational experience, map learning, map using and interpretation, spatial judgements based on a memorized map, and navigation in a novel environment based on a memorized map.

Good mappers performed more accurately than poor mappers in learning a novel environment, learning maps, and making spatial judgements based on a memorized map. Map using, map interpretation, and navigation tasks did not distinguish poor from good. Relative to poor mappers, good mappers are better able to encode and retain spatial information in memory and to mentally transform or manipulate spatial information to make spatial judgements. The authors hypothesize that spatial visualization and visual memory abilities may underlie these differences.

Individual differences in cognitive mapping skills cannot be attributed to differences in intelligence, memory ability, age, or experience. Thus, the authors assumed that any group differences were reflections of differences in skill at processing spatial information. Several distinctions between good and poor mappers are suggested:

1. Good mappers skills extend beyond tasks that require spatial learning information from direct experience. Good mappers may do better on any task that requires the acquisition of knowledge about large scale space, regardless of the source of the knowledge.

2. Poor mappers seem less able to encode and retain supplementary map information.

3. Poor mappers use inaccurate or unreliable computational procedures to produce spatial judgements.

4. Good mappers appear to be superior at acquiring and using procedural knowledge and they are better at acquiring and using survey knowledge from a map (as opposed to procedural knowledge).

The following were the general conclusions:

1. Skilled cognitive mappers excel at encoding procedural knowledge from the environment when navigating.

2. Skilled cognitive mappers excel at encoding survey knowledge from maps.

3. Skills mappers excel at computing spatial judgements from stored knowledge.

On the other hand, poor mappers performed as well as skilled on several tasks that relied on perceptual processes and simple knowledge retrieval rather than on knowledge acquisition or mental computation.

Hutchins, E. (1983). Understanding Micronesian navigation. In D. Gentner & A. L. Stevens (Eds.), Mental models (pp. 191-225). Hillsdale, NJ: Erlbaum.

This article discusses noninstrumental navigation in Micronesia. These sailors travel long distances out of sight of land. The mental model employed by them has them at the center with the islands moving past them, rather than the typical western view of the global perspective.

Larkin, J. H. (1983). The role of problem representation in physics. In D. Gentner & A. L. Stevens (Eds.), Mental models (pp. 75-98). Hillsdale, NJ: Erlbaum.

The author argues that the process of mentally simulating events is extended and refined in a skilled scientist and becomes a sharp and crucial intuition that can be used for solving difficult problems.

Expert and novice problem-solvers construct different representations of the problems. A naive representation held by a novice is composed of familiar objects that appear in the problem, and is developed through operators that correspond to developments that occur in real time. An expert also has this ability, however, their physical representation also contains entities, such as force and momenta, that have meaning in the context of formal physics. The latter representation is developed by operators according to the laws of physics.

The two representations are similarly built by taking relational information from the problem. Both use rules of inference to generate new information.

Naive and physical (one held by an expert, which contains entities such as force) representations are contrasted.

Naive	Physical
• "familiar" entities	• physical entities
• simulation inferencing (follows time flow)	• constraint inferencing
• distant from physics principles	• closely tied to physics principles
• tree structure, single inference sources	• graph structure, redundant inferences sources
• diffused properties of entities	• local properties of entities

The differences in the representations are in the kind of entities involved and in the rules of inference used to generate new information.

Larkin, J. H., McDermott, J., Simon, D. P., & Simon, H. A. (1980a). Expert and novice performance in solving physics problems. Science, 208, 1335-1342.

This paper opens with an interesting discussion about explanations of unexplained phenomena. Superior problem solving skill is explained by calling it talent, intuition, or imagination.

The authors state that the bulk of the research being done to explain the human information processes that underlie expert performance has taken verbal accounts from experts and novices as its data base. This method gives the researcher observations every second or so, but the critical human information processes that need to be understood take perhaps 10/1000 of a second. This incongruity requires a good deal of induction to test various hypotheses.

The authors feel that it is possible to develop and test theories as computer programs that simulate human information processing.

The data used is based on protocols and computer simulations developed from them. The authors state that their explanations are "operational and do not depend on vague, mentalistic concepts."

For the authors, the most obvious difference between experts and novices is the vast amount of information retained by the expert. Two areas in need of explanation are the quantity of information held by the expert and how it is stored in long-term memory.

Research done in the area of chess has given estimates for the retention of a master player at [illegible]0,000 chunks of familiar patterns. This is roughly equivalent to the number of words in the vocabulary of a college educated person.

The mental representation of something in human memory is made up of an organization of nodes connected by links, called a list structure.

STUDENT, a computer program, was able to translate verbal statements into the language of mathematics. This is one critical component needed to be skillful at solving physics problems.

The authors discuss some work done in the domain of kinematics. Experts solved the problems much faster than the novices, and in contrast to the novices, worked the problems forward--from the givens to the unknown. The experience of the experts allows them to take this less sophisticated route to the answer. The expert seemed to have progressed through the problem in leaps, putting the proper variables into the proper equations and obtaining an answer all in one step; while the novice had to plod through the problem step-by-step. The authors use an analogy between an interpretive execution of a computer program and a compiled execution to illustrate this.

The authors have created a program that solves various dynamics problems. The main stages of expert problem solving are stated as:

1. If the problem is not accompanied by a diagram the expert will draw one.

2. A tentative selection of a set of principles to use from which the expert will build an abstract problem representation containing physical entities relative to those principles.

3. The expert will represent the problem as a set of equations.

In the various domains studied, the common prerequisite for expert skill is considerable knowledge. Large numbers of patterns serve as an index to guide the expert in a fraction of a second to the relevant sections of his stored knowledge.

McGee, M. G. (1979). Human spatial abilities: Psychometric studies and environmental, genetic, hormonal, and neurological influences. Psychological Bulletin, 86(5), 889-918.

The purpose of the article is threefold:

1. To summarize psychometric studies of human spatial abilities.

2. To examine the consistencies and disagreements relating to the hypothesis that sex differences in various aspects of perceptual-cognitive functioning (e.g., mathematics, field-dependence/field-independence) are a secondary consequence of differences with respect to spatial visualization and spatial orientation abilities.

3. To review the literature with reference to environmental, genetic, hormonal, and neurological influences that interact in producing individual variation in spatial test scores.

An important emphasis of recent factor analytic research has been disentangling various subabilities that characterize the spatial factor of problem-solving. The available evidence demonstrates the existence of at least two spatial factors, visualization and orientation. Visualization is the ability to mentally manipulate elements of a pattern, while orientation is the ability to determine the objects position with respect to one's body.

The following qualifications need to be made regarding factor analytic studies of spatial abilities:

1. After 70 years of research, there is still vast disagreement about how best to classify standard tests of spatial abilities.

2. The influence of test-item difficulty on factor structure needs to be explored further; visualization test items are usually more difficult than orientation items.

3. Spatial tests consisting of both two- and three-dimensional items are used with equal frequency, but little is known about how dimensionality contributes to the factor structure of spatial tests.

4. Studies showing positive correlations between tests of spatial visualization and orientation illustrate the need for further factor analytic research to clarify the specificity of the visualization and orientation factors.

Six conclusions are warranted.

1. At least two distinct spatial abilities exist, visualization and orientation.

2. These abilities (visualization and orientation) are more highly correlated with success in a number of technical, vocational, and occupational domains than is verbal ability, making them important variables in applied psychology.

3. Sex differences in various aspects of perceptual-cognitive functioning are a secondary consequence of differences with respect to visualization and orientation abilities.

4. Sex differences on tasks requiring these abilities do not reliably appear until puberty.

5. Spatial abilities are known to be influenced almost as much by genetic factors as is verbal ability in all populations studied.

6. The development of sex differences in spatial skills are related to sex differences in the development of hemispheric specialization.

Teaching and Learning Physics

Champagne, A. B., Klopfer, L. E., & Anderson, J. H. (1980). Factors influencing the learning of classical mechanics. American Journal of Physics, 48(12), 1074-1079.

The most often explored variables that may contribute to success in learning physics are listed below:

1. Mathematical skills.
2. General level of cognitive development.
3. Specific cognitive processes.
4. Content preconceptions.

Mathematical skill is only one of several factors necessary to learning physics, and scoring highly on a math test is no guarantee of success in physics.

The issue considered here is cognitive development. A Piagetian approach is used to describe the interaction of mathematical skills with reasoning. An information-processing approach is used to analyze and specify the cognitive skills required to solve certain physics problems.

The authors note that other researchers have investigated the preconceptions that students bring with them with regard to physics. The wide diversity of situations shown here, in which this system of preconceptions surfaces, is indicative of its pervasive nature.

This particular paper attempts to investigate the combined effect of conceptions about motion, mathematical skills, and reasoning skills on a well-specified measure of achievement in classical mechanics. A preinstructional assessment of the students was obtained using three instruments:

1. A demonstration, observation, and explanation (d.o.e.) of motion test, which measured preconceptions about motion.

2. A logical reasoning test.

3. A mathematical skills test.

The results were the mechanics achievement score correlated significantly with only the d.o.e. test and reasoning and math test scores, not with the sex or previous education of the subject. Even so, the d.o.e. score was not a strong predictor of success in learning mechanics.

The authors conclude that students start out with a rich network of common-sense beliefs about motion, which can be characterized by four rules:

1. A force, when applied to an object, will produce motion.

2. Under the influence of a constant force, objects move with constant velocity.

3. The magnitude of the velocity is proportional to the magnitude of the force and any acceleration is because of increasing forces.

4. In the absence of forces, objects are either at rest or, if they are moving (because they stored up momentum while previous forces were acting), they are slowing down (and consuming their stored momentum (i.e., impetus)).

In the everyday frictional world, these rules provide a reasonable approximation of the behavior of objects.

Chi, M. T. H., Feltovich, P. J., & Glaser, R. (1981). Categorization and representation of physics problems by experts and novices. Cognitive Science, 5, 121-152.

This article examines the differences between the way an expert and a novice solve physics problems. The hypothesis guiding their present research is the representation of a problem is "constructed in the context of the knowledge available for a particular type of problem. Thus, expert-novice differences may be related to poorly formed, qualitatively different, or nonexistent categories in the novice representation." (p. 121)

The authors initially examined problem-sorting. They asked eight doctoral students and eight students who had just completed an introductory mechanics class to categorize

24 problems from a physics text. The two groups did not differ in the number of categories produced and each subject placed most of the problems into four groups. Furthermore, the pattern of the sorts appeared stable across time. An interesting outcome of the sorting was that the experts actually took about 45 seconds longer per problem to finish the task on the first trial, yet on the second trial, the sorting took them about 2 or 3 seconds less per problem, on the average, than the novices.

A qualitative analysis of the resulting patterns showed that the novices based their sorting decisions on "surface structures." These consisted of the objects appearing in the problem, the literal terms mentioned, and the configuration described in the problem. It was difficult to determine what the physicists based their decisions on. It appeared, however, that the basis was the major physics principle that would solve the problem.

A second study confirmed these findings. The problems that appeared to be similar on the surface were grouped together (across major physics principles) by the novice group. The authors discuss their findings in terms of the proposed "stages" of representation presented by McDermott and Larkin (1978).

The authors claim that the categories formed by the two groups "elicit a knowledge structure that functions in the representation of a problem, and that at least for experts, this includes potential solution methods." (p. 151)

Clement, J. (1982). Students' preconceptions in introductory mechanics. American Journal of Physics, 50, 66-71.

This study examines problem-solving data from written tests and taped interviews. The author recognizes the existence of inherent "conceptual primitives," which include key concepts, fundamental principles, and models. It is suggested that these root concepts may cause learning difficulties for the student. Furthermore, it is noted that difficulties with these primitives may result from "intuitive preconceptions," which the student has developed on his or her own before entering courses.

The author discusses a qualitative preconception concerning the widely studied relationship between force and motion (force equals mass times acceleration, or $F = MA$). An understanding of this formula is difficult, because friction is generally not recognized as a force by the student.

The author chose problems of minimum difficulty to study these misconceptions and isolate the sources of error. Their first problem involves labeling the various forces that act on a swinging pendulum. Many of the students who answered the problem incorrectly included a force that was within the swinging ball that causes the ball to swing back up. The author labeled this the "motion implies a force" misconception. This falsehood shows up in pre-Newtonian physics as an impetus force.

To further study this misconception, he designed a problem that restricted the range of answers. Students were asked to label the various forces present on a diagram depicting a tossed coin. Nearly everyone, even some students who had college physics, labeled a force that was causing the coin to be carried up through the air. This was taken as further evidence for the "motion implies a force" misconception.

A third problem consisted of tracing the path of a rocket in motion with its engine off and the rocket traveling sideways. At one point, the engine is fired for 2 seconds and quickly shut off. The student is asked where the rocket will go. Again, the "motion implies a force" preconception surfaces. Most answers given had the rocket traveling at a 45 degree angle from its original path while the rocket engine was on. When the engine was turned off, they depicted the rocket as resuming its original direction. The author stated that Galileo had made similar arguments in his tome De Motu.

To study the effects of a physics course on these misconceptions, 43 students were given the same problem after completing an introductory course in mechanics. It was found that the scores for this group were not much better, especially for the coin problem. For most of the students, the "motion implies a force" misconception is highly resistant to change.

de Kleer, J., & Brown, J. S. (1983). Assumptions and ambiguities in mechanistic mental models. In D. Gentner & A. L. Stevens (Eds.), Mental models (pp. 155-190). Hillsdale, NJ: Erlbaum.

This study investigates the structure of mental models of physical devices. The authors state that complex devices are generally composed of simpler components. The device they choose to discuss is a buzzer. A suggested qualitative simulation is expressed as follows:

> The clapper switch of the buzzer closes, which causes the coil to conduct a current, thereby generating an electromagnetic field which in turn pulls the clapper arm away from the switch contact, thereby opening the switch, which shuts off the magnetic field, allowing the clapper arm to return to its closed position, which then starts the whole process over again. (p. 156)

The authors distinguish four related ideas about qualitative reasoning:

1. Device topology--a representation of the structure of the device.
2. Envisioning--an inference process that determines its process.
3. Causal model--a description of component interaction.
4. Running--a run through the causal model to determine the specific function of the device.

The authors discuss a problem-solving method for envisioning, called propagation. This consists of starting with a single noncausally produced event and then looking at nearby components to examine the results. This method is contrasted with the method of relaxation, which begins by assigning all possible qualitative values to all the interacting quantities. They suggest that a "valid" simulation should be:

1. Consistent--have no internal contradictions.
2. Corresponding--envisioning the same as actual observing.
3. Robust--useful in unusual situations.

The authors point out that because the quantities referenced by the component models are qualitative, detailed distinctions are impossible. It is also not possible to determine the ordering of events.

Because of the inherent ambiguities involved in a qualitative simulation (i.e., Is the spring stronger than the magnetic filed in the suggested model?), certain assumptions must be introduced. You must assume that the spring is stronger than the magnetic field and also assume that it is weaker than the field.

The authors discuss some implications of their theory of qualitative simulation. They distinguish three kinds of learning that might be engaged while acquiring an understanding of a machine:

1. Establishing a connection between structure and function.
2. Making implicit assumptions explicit.
3. Storing the information.

In conclusion, the authors state the need for methodological constraints in constructing a learning theory that has generality or validity.

diSessa, A. A. (1983). Phenomenology and the evolution of intuition. In D. Gentner & A. L. Stevens (Eds.), Mental models (pp. 15-33). Hillsdale, NJ: Erlbaum.

This article is about a special layer of primitive notions that exists without any true justification. This layer of knowledge serves as the foundation for a system of reasoning. the author calls these notions "phenomeno-logical primitives," or p-prims. The author states: ". . . in the course of learning, physics-naive students begin with a rich but heterarchical collection of recognizable phenomena in terms of how they see the world and sometimes explain it. These are p-prims." Some are compatible with formal physics and are therefore encouraged and acquire a higher priority than the others. Along the same lines, some p-prims lose status.

The empirical basis for this work came from interviews with four MIT students enrolled in freshmen physics.

They were asked, for example, "If a ball is dropped, it picks up speed and hence kinetic energy. When the ball hits the floor, however, it stops. At that instant, there is no kinetic energy since there is no motion. Where did the energy go?"

The focus of the question is, "What is it that pushes the ball back up into the air?" One student tended to center her discussion around rigidity and springiness. These were her p-prims; both seemed to have a high priority.

A physicist would tend to have a much lower priority attached to the concept of rigidity. He would have a strong understanding of physical mechanisms that includes the idea that looking at the world in terms of forces is fundamentally the proper explanation for physical phenomena. For him, rigidity would be irrelevant. Springiness, however, would have a high priority in that it is a more powerful explanatory concept.

The author discusses a structure for the concept of p-prim priority. First, cuing priority refers to the value of the idea, and reliability priority refers to the p-prims resistance to abandonment. Second, priorities are context dependent.

The author also discusses OHM's p-prims. This consists of an impetus, a resistance, and a result. It is suggested that this is a commonly used high priority p-prim. As an example of its widespread use, it appears in a physics text as an aid to understanding that current is equal to the applied voltage divided by the resistance (I = E/R).

The author discusses some persistent false intuitions, such as:

1. Dying away--ignoring friction and the belief that dying away is the natural way of things. This leads to the popular misconception that a constant force is needed to maintain a constant velocity.

2. Force as a mover--a force causes motion in the direction of force, regardless of the previous motion.

3. Force as a spinner--the belief that pushing an object off-center causes spinning, and because such a force causes both spinning and moving, its effect on moving should not be as great as if the force were only applied to moving.

Egan, D. E., & Grimes-Farrow, D. D. (1982). Differences in mental representations spontaneously adopted for reasoning. Memory and Cognition, 10(4), 297-307.

The main question addressed is whether different people spontaneously adopt different ways of mentally representing problems. Two conclusions follow from the first experiment:

1. Retrospective reports following a reasoning task can be used to classify subjects into groups.

2. These categories tentatively appear to have some validity.

These results suggest that no single theory of problem-solving can account for the data unless that theory includes an account of why *individual subjects adopt one* representational scheme rather than another. The results also suggest that a score on a reasoning task may at least partially indicate what mental representation an examinee adopted for an entire set of problems.

Fuller, R. G., Karpus, R., & Lawson, A. E. (1977, February). Can physics develop reasoning? Physics Today, 23-28.

Certain patterns of reasoning appear to be more common among physicists, such as:

1. Focusing on the important variables, such as force.
2. Propositional logic.
3. Propositional reasoning.

Physics test questions may be examined from a developmental (read Piagetian) point of view. This stage concept may be more useful for classifying reasoning patterns than for describing the overall intellectual behavior of every particular person at a given time. Formal reasoning develops only through the process of self-regulation. Concrete reasoning is thus a prerequisite for the development of formal reasoning. Self-regulation = assimilation, or taking in a situation in terms of the present reasoning abilities, + accommodation, which entails an analysis of the situation to locate sources of difficulty (facts that don't agree with present reasoning abilities) and formation of new hypotheses and plans for solving strategies.

The development of reasoning has two requirements:

1. Exploratory experiences with the physical world.

2. Discussion and reflection on what has been done, what it means, and how it fits, or does not fit, with previous patterns of thinking.

Fuller, R. G. (1982, September). Solving physics problems--How do we do it? Physics Today, 43-46.

The author states that he sees three areas of problem-solving research that are of particular interest to physicists: (1) misconceiving natural laws, (2) processing information, and (3) constructing solutions. He states that for physics teachers, the implications of current research is that the minds of the students are not "empty vessels into which professors pour the knowledge of physics equations, of relationships, and of problem-solving strategies. It is a jungle of Aristotelian and even pre-Aristotelian ideas about nature." (p. 44)

He feels that false ideas arise because the world in which we live seems to operate along the lines of a non-Newtonian system. Everyday experiences, with the force of friction, interfere with the acquisition of a Newtonian understanding of motion. When the student is confronted with an explanation of Newtonian physics in the classroom setting, the author suggests that the information is placed in a special category for useless ideas to be learned only for a particular class.

Fuller states that there are roughly two groups of researchers who have been studying problem-solving. The first group has looked at information processing and attempted to describe the way in which people solve finite and particular problems. The second group, the constructivists, have concentrated on the area pioneered by Piaget, looking more toward abstract and creative thinking.

The first group has compared expert and novice problem-solvers and they have found that the experts appear to approach problems through a successive series of refinements. The physicists, for example, have organized their knowledge into sizable, coherent chunks, which are more accessible than separate items of knowledge.

The second group, the constructivists, have focused more on the conscious steps of problem-solving. They tend to deal with the internal mental processes by which one builds problem-solving strategies, and how they are refined and changed as the individual ages and learns new material. This group emphasizes a philosophical understanding of knowledge and its development.

He goes on to discuss the work of Piaget. Piaget suggested a dynamic interaction model of assimilation-accommodation equilibration as the way by which knowledge and problem-solving methods are constructed. According to this model, it is a self-regulating process. One's experience of nature through sensory input is compared with one's understanding of nature through one's use of mental structures. When these do not match, disequilibration occurs. Piaget argues that this makes individuals uneasy, causing them to naturally seek new information or a reorganization of what they do understand.

The author discusses several potential teaching strategies.

Kosslyn, S. M., Cave, C. R., Forbes, Z. E., & Brunn, J. L. (1983). Imagery ability and task performance (Technical Report No. 2). Waltham, MA: Brandies University.

The authors tested 50 subjects on a battery of imagery tasks and showed that subjects differed in their ability to perform specific imagery operations (such as image scanning, rotation, and generation) used in a previous study. The generality and reliability of the imagery analyses, described in that study, were examined by retesting 14 of the same subjects in a new imagery experiment conducted a year later using different tasks. The new tasks were designed to operationalize the components of visual imagery processes discovered in the previous experiment, and each subjects' performance was predicted by the previous performance.

The authors wanted to know whether people differ in terms of a general, undifferentiated imagery ability or in terms of a set of relatively independent abilities. They found the second possibility received support from the data. In the present study, the authors expected scores on the new tasks to be correlated only with the earlier scores in tasks putatively requiring the same underlying processing.

The results were that of the 14 cases where correlations were expected, 12 were obtained, and of the 12 cases where correlations were not predicted, only 2 were observed. There were some unexpected results; subjects showed great variability in the easy conditions, not just the harder ones. Average people are generally very poor at imagery operations, as opposed to college students, who rotated images about three times as fast as these subjects recruited via newspaper ads. A second surprise was the tendency to find negative correlations with error rates while finding positive ones with times, suggesting a speed-accuracy trade-off. Such component-specific trade-offs suggest much independence in the operations of the components and also suggest that people may have strategic control over the operation of specific processing components.

Two conclusions can be drawn from these results:

1. People do not differ in terms of specific underlying imagery components; it was not found that subjects generally did poorly or well in all conditions.

2. The patterns of correlations provide good evidence that such individual differences persist for at least a year and generalize across very different tasks.

Minstrell, J. (1982). Explaining the "at rest" condition of an object. The Physics Teacher, 20, 10-14.

The author of this paper is a high school physics teacher. He reviews one of his lectures dealing with the at rest condition of an object. As a result of his work, he suggests several things for a teacher to do to aid students' attempts at understanding the forces involved:

1. Prepare an engaging social context.
2. Juxtapose several instances of the case.
3. Allow students to argue for the simplest explanation.

He bases his instruction primarily on concept development.

Trowbridge, D., & McDermott, L. (1980). An investigation of student understanding of the concept of velocity in one dimension. American Journal of Physics, 48, 1020-1028.

Several motion tasks, developed by Piaget, were administered to the subjects. The subjects had no difficulty with these. Other experimental conditions revealed an interesting error in a speed comparison task. Errors on this problem were invariable due to the use of a position criterion in determining the relative velocities of two moving objects. Consistently, being ahead was seen as being faster, and being behind was seen as being slower. The students making this kind of mistake were still able to give a reasonable explanation of velocity.

The authors feel they have shown that, "prior to instruction, the student typically has a repertorie of procedures, vocabularies, associations, and analogies for interpreting motion in the real world." Finally, suggestions for instruction are offered.

Trowbridge, D., & McDermott, L. (1981). An investigation of student understanding of the concept of acceleration in one dimension. American Journal of Physics, 49, 242-253.

The focus of this study is the qualitative understanding of acceleration as the ratio of the change in velocity divided by the change in time (dv/dt). Results obtained from the study show a widespread inability to apply the concept of acceleration in a physical situation. This is interesting because many of these students could reasonably define the concept. Perhaps the criterion for an acceptable definition of the concept was too lenient.

White, B. Y. (1983). Sources of difficulty in understanding Newtonian dynamics. Cognitive Science, 7, 41-65.

This study contains data generated from responses obtained from 40 high school students who had taken a physics class. The subjects were asked to solve a series of motion and force problems. Although most of the students had studied Newton's Laws, most of them could not correctly answer questions involving the application of the specific theories.

White suggests that there is no single belief or misconception that accounts for the diversity of errors. Some of the erroneous, inconsistent ideas held include (1) incorrect notions about force and motion because of the often overlooked force of friction, (2) partially understood information from physics classes, and (3) the application of irrelevant principles from scaler arithmetic.

Impetus/Aristotelian Theories

Clement, J. (1983). A conceptual model discussed by Galileo and used intuitively by physics students. In D. Gentner & A. L. Stevens (Eds.), Mental models (pp. 325-340). Hillsdale, NJ: Erlbaum.

Clement mentions two interesting techniques employed by Galileo in his works. First was his use of qualitative thought experiments in his presentations. Second was his inclusion of theories that he considered to be wrong. The author notes that Galileo probably recognized the difficulty with which his new ideas would be accepted and thus simply presented mathematical equations as do modern physics texts.

Like Galileo's colleagues, todays student of physics has a view of the world, which is not necessarily correct and is highly resistant to change. Most noticeably, many students have an alternative mental model of the relationship between force and motion. The model they generally use does not include the force of friction, which plays an important part in the real world.

The author uses three problems (pendulum, a tossed coin, and a traveling rocket) to examine the intuitive models held by students.

After studying the error patterns, he summarizes what appears to him to be the most common characteristics of the "motion implies a force" preconception:

1. Continuing motion, even at a constant velocity, can trigger an assumption of the presence of a force in the direction of motion that acts on the object to cause the motion.

2. Such invented forces are especially common in explanations of motion that continues in the face of an obvious opposing force. In this case the object is assumed to continue to move because the invented force is greater than the opposing force.

3. The subject may believe that such a force 'dies out' or 'builds up' to account for changes in an object's speed. (p. 335)

He points to the wide variety of situations in which these beliefs surface as evidence that it is a major source of difficulty in understanding the principles associated with the equation F = MA. He goes on to suggest various teaching strategies to deal with these faulty mental models. One approach is to design laboratory activities that require qualitative predictions about the various forces and magnitudes involved rather than simply cranking through the mathematical formulas.

diSessa, A. A. (1982). Unlearning Aristotelian physics: A study of knowledged based learning. Cognitive Science, 6, 37-75.

This is a study done on elementary school students learning to control an object animated on a computer. The results reveal a heavy emphasis on Aristotelian notions; such as, things should move in the direction that they were last pushed. The object on the computer reacted to commands according to Newton's laws.

Two model games were provided to the students. The first was simply to direct the object to a target with rights, lefts, and kicks. The students introduction was brief--consisting of the commands and a demonstration using a tennis ball and a mallet on a table.

The students, although chosen to represent a wide spectrum of competence, showed a remarkable similarity in their attempts to control the object. All the students tried to make a 90 degree turn by simply aiming and giving the object a kick in the proper direction, ignoring the initial motion.

Most subjects said the machine was broken when they saw that the resulting path was a compromise of the two forces involved--the kick and the motion of the object before the kick.

Statements involving velocity were not observed in the youngsters, but were in older subjects. This is seen as a major turning point toward an understanding of Newtonian physics.

To further study the evolution of this particular knowledge, the author had an MIT freshmen who had taken both high school and college physics play the game. Her strategy was remarkably similar to that of the 11- and 12-year-old children. For a time, she could not relate the game to any of the classroom physics she had learned.

The author goes on to develop a "genetic task analysis," from the pooled data, of how one might come to understand Newtonian physics. The intent of this analysis is to identify components of pre-existing knowledge that can, or do, become involved in solving the problem.

The sequence starts with the realization that aiming does not effect motion, and ends with the ability to control velocity. It is a path that is seemingly natural. The author goes on to say, experiences in the real world do not necessarily teach Newtonian physics. A non-Newtonian explanation; such as, "kicking in the direction of intended motion," can appear plausible.

McCloskey, M. (1983a, April). Intuitive physics. Scientific American, 248(4), 122-130.

The author devised a simple task in which intuitive ideas might influence the methods of completion. He states that the misjudgments about the paths of moving objects are systematic, arising from a general, coherent theory of motion that closely resembles the pre-Newtonian theory of impetus. This theory states that motion must always have a cause. The cause appears to represent an internal impetus that would gradually dissipate.

Many students asked to solve a problem dealing with motion state the impetus theory rather explicitly when asked to explain their answers.

The marked similarity between modern students and medieval philosophers suggests that the impetus theory is a natural outcome of experiences with motion. Sometimes the frame of reference may confuse the observer. Experimentation with a moving frame of reference did not necessarily substantiate this, but this is still a possible hypothesis.

McCloskey, M. (1983b). Naive theories of motion. In D. Gentner & A. L. Stevens (Eds.), Mental models (pp. 299-324). Hillsdale, NJ: Erlbaum.

McCloskey discusses various naive beliefs about the motion of objects and compares them to pre-Newtonian beliefs.

McCloskey, M., Caramazza, A., & Green, B. (1980). Curvilinear motion in the absence of external forces: Naive beliefs about the motion of objects. Science, 210, 1139-1141.

One would assume that common experiences demonstrate to the individual basic physics principles and that this would lead to an understanding of the behavior of moving objects. This is not the case. Apparently, perceptual exposure to objects in motion can, for many people, be very misleading. Everyday experience with moving objects leads to a belief, shown to be highly resistant to change, that an object set in motion will eventually come to a stop in the absence of an obvious external force. Several experiments substantiate this fact.

The focus of the present paper is to assess the understanding of the principle that objects move in a straight line in the absence of external forces. The subjects were 50 university students, half having received formal instruction in physics. Each subject was given 13 relatively simple problems consisting of a drawing and instructions.

A surprising percentage of the students depicted an object moving through a curved tube, coming out of the tube, and continuing its curved path. This general type of error was consistent across subjects.

The authors state that these beliefs are amazingly similar to the medieval theory of "impetus." They suggest that educators should not assume their students are merely lacking the correct information. By not addressing the misconceptions, instruction may only provide the student with new terminology to express his errors.

McCloskey, M., & Kohl, D. (1983). Naive physics: The curvilinear impetus principle and its role in interactions with moving objects. Journal of Experimental Psychology: Learning, Memory, and Cognition, 9, 146-156.

The authors acknowledge the existence of recent studies showing common incorrect beliefs about motion. They question the origin of the many misconceptions held by students. Findings in the problem-solving literature suggest that performance on mildly abstract problems is substantially worse than performance on identical problems that are more concrete.

It is hypothesized that unrealistic tasks may simply fail to tap the appropriate knowledge. Many people may have accurate beliefs about the motion of objects, but it may be in a form that is not readily applied within the context of the problems presented to the students in previous studies.

The authors point to research that indicates a large percentage of the subjects tested about the motion of objects could identify the correct answer. This suggests that people may have an accurate perceptual knowledge of motion. Paper-and-pencil problems may fail to activate this knowledge.

To test this hypothesis, the authors tested three groups of students. The first group was simply shown a diagram of a ball and string problem (a ball is swinging in a circular motion at the end of string and the string is cut--where will the ball travel?). For the second group, the procedure was the same except these students also viewed a dynamic presentation of the rotating ball and string simulated on a computer. Lastly, in the third group, the students viewed not only the rotating ball and string on the computer, but also six alternative trajectories to choose from. For each alternative, the ball was shown rotating, the string would be cut, and the ball would fly off along the appropriate path.

The results of the three conditions replicated previous findings when viewed across conditions. Interestingly, performance did not differ significantly across the three conditions. Dynamic presentations of the problems did not improve performance. Performance was found to be greater with increasing expertise in physics. The authors take these findings as evidence against the hypothesis of accurate perceptual knowledge.

An attempt to replicate their unexpected findings was successful. Interestingly, in this second experiment, twice as many of the women gave incorrect answers.

To further substantiate their findings, the authors designed a task that they felt might better tap the supposed reservoir of accurate perceptual knowledge concerning the motion of objects. They purposely designed a problem to be as concrete as possible, with little if any resemblance to a textbook physics problem. The results show that even with interactions involving actual objects, students demonstrate a belief in a "curvilinear impetus principle."

McCloskey, M., Washburn, A., & Felch, L. (1983). Intuitive physics: The straight-down belief and its origin. Journal of Experimental Psychology: Learning, Memory, and Cognition, 9, 636-649.

The purpose of this paper is to study the properties and source of a common misconception concerning moving objects. The authors address these questions within the context of the "straight down" belief.

Basically, this is the idea that carried objects drop straight down. The authors propose that this belief is developed as a result of a perceptual illusion.

The results showed that the straight down belief surfaces not only in problems of a static type, but also in dynamic, concrete problems in which the subject was the carrier.

To search for the source of this misconception, the authors designed an experiment on a computer that depicted a carried object being dropped from a moving box. In some of the trials the moving box was not shown, only the falling object. The obtained results showed that the presence of the moving box adversely affected the subjects' perception of the path of the object. The moving frame of reference resulted in misperceptions of the trajectories.

To further examine these findings, the authors present subjects with a videotape of a walking person dropping an object. Seventy-eight percent of the responses stated that the object fell backwards or straight down. As an explanation for the source of this misconception, the authors offer the hypothesis of "seeing is believing." Misperceptions lead to misconceptions!

Viennot, L. (1979). Spontaneous reasoning in elementary dynamics. European Journal of Science Education, 1, 205-221.

Although it is generally believed that we only know what we have been taught, this author contends that we all have an intuitive sense of physics. Furthermore, this "intuitive physics" tends to interfere with attempts of teachers to effectively inform their students. He mentions that many people believe in a linear relation between force and velocity, rather than one between force and acceleration. This is similar to the "impetus" theory.

To study this problem, he uses several simple mechanical systems with their motion frozen. For one question the system is a set of juggler's balls captured in flight, all at the same height. In a similar version, the system is a set of three masses oscillating on the ends of vertical springs suspended from the ceiling, again from the same height. The students are asked whether the forces acting on the balls and the masses are identical at the instant shown. The correct answer is that they are. The forces that are taken into account depend solely on the positions of the bodies and not on their motion.

These experiments and others done by the author tend to suggest that there is a commonly held belief system held by third year British university students. This can be expressed as follows:

1. If velocity = 0, then force = 0.
2. If velocity < = > 0, then force < = > 0, even if acceleration = 0.
3. If the velocities are different, so are the forces.

He goes on to describe plausible notions a student may have about the equation F = MA.

1. Force of interaction--this is a function of the position of a moving body.

2. Supply of force--this may be thought of as the force that keeps an object in motion.

Analogical Reasoning

Gentner, D. (1980). The structure of analogical models in science (Technical Report No. 4451). Cambridge, MA: Personnel and Training Research Programs.

This paper proposes a structural characterization of good science analogy using a theoretical approach in which complex metaphors and analogies are treated as structure-mappings between domains. The author is interested in what makes some analogies useful in scientific thinking and others useless or harmful. The author attempts to define the differences between good and poor explanatory analogies by proposing a structural characterization of good science analogy. The approach here is to present a theory in which complex metaphors and analogies are treated as "structure mappings" between domains, and within this frame work, comparisons are made to help delineate structural characteristics of good scientific analogy. Then metaphor and analogy are contrasted with literal similarity, and explanatory-predictive analogy is contrasted with literary expressive metaphor. Then, within science, good explanatory analogy is contrasted with poor explanatory analogy.

This characterization of scientific analogies leads to a consideration of the processes of development of a science model from an initial comparison. To illustrate these points, analogies of historical importance are analyzed. Nonliteral similarity comparisons, including metaphors, similes, and models are all referred to as "analogies." The author then proposes the characterization of a metaphor or analogy as a structure-mapping between a known "base system" (in terms of which the system to be understood is described), which is often familiar and perhaps visualizable, and the "target system," which is the system to be understood. Objects in the base system are mapped onto objects in the target system. This allows the predicates of the base to be applied to the target domain. This characterization assumes that identical operations and relationships hold among nonidentical things. This requires viewing both domains as systems of objects and relationships. The objects need not necessarily be concrete, but must at least be separable components.

This conceptualization is closely related to Rumelhart's "schema"--a propositional network of nodes (objects) and predicates (attributes or relations). The difference between structure mappings and schema is that in structure mappings relational predicates, and not object attributes, carry over in analogical mappings--the same relations between different objects.

An overlap in relations is necessary for the perception of similarity between two domains. An overlap in both object attributes and inter-object relationships is seen as literal similarity (a helium atom like a neon atom). An overlap in relationships but not objects is analogical relatedness (a hydrogen atom is like the solar system). Finally, overlap in objects but not relationships is seen as temporal relatedness, not as similarity (limestone is related to lime and carbon dioxide). All the above implies that literal similarity versus metaphorical relatedness is a continuum, not a dichotomy--given that two domains overlap in relatedness, they are more literally similar to the extent that their component object-attributes also overlap.

An analysis of subjects rating different analogies lend support to the claim that structure-mapping is a general processing heuristic available to subjects in a scientific context. This is also consistent with the idea that complex explanatory analogies are understood primarily as structure-mappings.

The author then pursues the question of what makes a good scientific analogy. The most obvious criterion is validity, or "Do equal relations hold for both systems?" This ignores the systems properties of analogy. This is why we turn to the structural qualities of a good science analogy. Gentner proposes some structural considerations that characterize good science analogy:

1. Base specificity--this arises even before analogy is defined, which refers to the degree that the structure of the base is explicitly understood.

2. Internal structural characteristics, such as clarity, which refers to the precision that the mappings can be traced (i.e., how exactly the base nodes map onto the target nodes and which predicates get carried across).

3. Richness--the quantity of predicates that are meant to be mapped, which refers to its predicate density.

Next, we consider the kinds of predicates mapped.

1. Abstractness--where in the structural hierarchy the mapped predicates are found, whether they are attributes or relations, and whether they are higher order or

lower order relations. First-order relations are relations among objects, while second-order relations are relations among first-order relations. The greater the proportion of higher-order relations the more abstract the mapping. Note that often there is a trade-off between abstractness and richness.

2. Systematicity of the mappings--the degree to which the relations mapped belong to a known mutually constraining conceptual system.

Next, we consider if the mapping is valid.

1. Validity refers to the truth value or correctness as applied to the target (it is assumed to be valid in base).

2. Target exhaustiveness refers to the proportion of the target relationships the model accounts for, how many of the significant relational predicates in the target can be mapped from the base. Base exhaustiveness refers to the extent to which the structure of the base domain is applicable to the domain and this complements target exhaustiveness.

3. Transparency is the ease with which it can be decided just which predicates from the base domain are to be applied in the target domain.

There is an external consideration: Scope refers to the number of different cases to which the model validity applies.

The next portion of the paper uses these structural distinctions to characterize a good explanatory-predictive analogy. Two contrasts are useful here:

1. Explanatory analogy (explain and predict) versus expressive analogy (to evoke or describe).

2. Good explanatory analogy versus poor explanatory analogy.

Then the author turns to expert versus naive models in science. Are people's naive models of science more like explanatory analogies or expressive analogies? What about expert models of science? The expert apparently has an abstract global model with broad scope, while the novice has a pastiche of rich, but only locally useful models. The experts' global models have a limited set of general operations and relationships; novices have great many locallv applicable predicates; experts models appear more systematic, novices less--ergo, naive models of science appear more like expressive analogies than do expert models.

Finally, the author turns to the development of models. Apparently, analogies start out rich and unclarified and require pruning and clarification to become good explanatory analogies. This process is referred to as predicate-strippine and it removes nonessential comparisons.

This framework is also useful in characterizing the structure of naive mental models people have about physical phenomena. These models appear to be more like expressive analogies than the analogies used by our expert subjects. This opens possibilities for research. For example, do expert models differ from novice models because of their greater experience with the topic area. or is it the knowledge of general modeling rules that distinguishes experts from novice, or both?

Gentner, D., & Gentner, D. R. (1983). Flowing waters or teeming crowds: Mental models of electricity. In D. Gentner & A. L. Stevens (Eds.), Mental models (pp. 99-129). Hillsdale, NJ: Erlbaum.

The paper explores the conceptual role of analogies. The authors cite two instances in which analogies can have genuine effects on a person's conception of a domain. First, they are often used in teaching. Second, working scientists often use them in theory development.

The stated purpose of the paper is the testing of the Generative Analogy hypothesis--"that conceptual inferences in the target follow predictably from the use of a given base domain as an analogical model." To test this, the authors must show that the inferences a person makes in a topic domain vary according to the analogies referred to. The topic domain chosen was electricity.

The obtained results do support the hypothesis. He found that those who viewed electricity as a flowing fluid understood better when questioned about batteries, while those who viewed electricity as moving objects understood better when questioned about resistors.

Greeno, J. G. (1983). Conceptual entities. In D. Gentner & A. L. Stevens (Eds.), Mental models (pp. 227-252). Hillsdale, NJ: Erlbaum.

This article deals primarily with the representation of problems. The focus is on the kinds of entities, or cognitive objects, that the system can reason about directly and that it continually includes. The author states:

> . . . a system reasons directly about an object if it has procedures that take the object as an argument. In this regard, entities can be distinguished from attributes and relations, which have to be retrieved or computed using the entities as cues or arguments. (p.228)

He uses the term ontology to refer to entities that are available for representing problem situations.

He hypothesizes that the ontology of a domain is significant because:

1. It is an important factor in forming analogies.
2. It enables the use of general reasoning procedures.
3. It provides efficiency.
4. It should be an important factor in planning.

Using these four hypotheses, he discusses examples in which the findings are interpretable. His second proposed function of conceptual entities is that they provide arguments on which general reasoning procedures can operate directly. Expert problem-solvers use representations in which forces, energies, and other abstractions are treated as entities. The problem from which he obtained protocols is ". . . an object is dropped from a balloon descending at 4 m/sec. If it takes 10 seconds for the object to reach the ground, how high was the object when it was dropped?"

To the author it is important, in classroom instruction, to include the conceptual entities that are needed to represent problems in a domain.

In another experiment, seventh grade students were given instruction in solving problems involving simple motion. The most effective instruction included both observational and computational training. The author interprets the findings as evidence for the idea that these students acquired representational knowledge in which distance, velocity, and duration were conceptual entities.

Norman, D. A. (1983). Some observations on mental models. In D. Gentner & A. L. Stevens (Eds.), Mental models (pp. 7-14). Hillsdale, NJ: Erlbaum.

The author opens with the obvious--that people's views depend on their conceptualizations. He proposes several general characteristics of mental models:

1. They are incomplete.
2. They are unstable.
3. They have no firm boundaries.
4. They are unscientific.
5. They are parsimonious.

Finally, he argues for the consideration of four distinct things during the study of mental models:

1. The target system.
2. The conceptual model of the target system.
3. The user's mental model of the target system.
4. The scientist's conceptualization of the mental model.

Young, R. M. (1983). Surrogates and mappings: Two kinds of conceptual models for interactive devices. In D. Gentner & A. L. Stevens (Eds.), Mental models (pp. 35-52). Hillsdale, NJ: Erlbaum.

This article examines the concept of a users conceptual model by taking a look at various mental models appropriate for several different designs of pocket calculators. The author lists several different kinds of models--strong analogy, surrogate, mapping, coherence, and others. He is primarily concerned with surrogate and mapping models.

His proposed criteria for a good conceptual model are (1) performance, (2) learning, (3) reasoning, and (4) design.

The users model should help explain these aspects of the use of the system.

Task/action mapping models best meet these criteria. They focus on the fact that the role of the users conceptual model is to mediate between the user and the device.

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